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Application of Staged Combustion and Reburning to the Co-Firing of Nitrogenated Wastes: Chemical and Biological Analyses

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16. ABSTRACT The paper gives results of an evaluation of a 0.6 MW precombustion chamber burner, designed for in-furnace NOx control and high combustion efficiency (CE) for high nitrogen content waste co-firing. The 250- to 750-ms residence time precombustion chamber burner mounted on a prototype water-tube package boiler simulator used air staging and in-furnace natural gas reburning to yield up to four stoichiometric zones. Natural gas doped with ammonia and No. 2 distillate fuel oil doped with pyridine were used to simulate high nitrogen content fuel/waste mixtures. Minimum NO emission levels correspond to about 85% reduction in NOx emissions compared to uncontrolled emissions from a conventional swirl burner mounted on a 0.7-MW commercial package boiler. CO emissions for these burner characterization tests indicated CEs >99%. The low NOx precombustor was then used to examine the co-firing characteristics of a nitrogenated pesticide containing dinoseb in a fuel-oil/xylene solvent. The dinoseb formulation as fired contained 6.4% nitrogen. NO emissions without in-furnace NOx control exceeded 4400 ppm (at 0% O2). When NOx controls in the form of air staging and natural gas reburning were employed, these emissions were reduced to <150 ppm (96% reduction). Average CO and total hydrocarbon emissions were typically <15 and 2 ppm, respectively.

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Combustion	Mutagens	Stationary Sources	21B 06E
Wastes		Staged Combustion	14G
Chemical Analysis		Reburning	07D
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Application of Staged Combustion and Reburning to the Co-firing of Nitrogenated Wastes: Chemical and Biological Analyses

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ABSTRACT

A 0.6 MW (2,000,000 Btu/hr) precombustion chamber burner, designed for in-furnace nitrogen oxide (NO_x) control and high combustion efficiency, was evaluated for high nitrogen content waste co-firing applications. The 250- to 750-ms residence time precombustion chamber burner mounted on a prototype water-tube package boiler simulator used air staging and in-furnace natural gas reburning to yield up to four stoichiometric zones. Natural gas doped with ammonia (NH_3) and No. 2 distillate fuel oil doped with pyridine (C_5H_5N) were used to simulate high nitrogen content fuel/waste mixtures. Minimum nitric oxide (NO) emission levels correspond to approximately 85% reduction in NO_x emissions compared to uncontrolled emissions from a conventional swirl burner mounted on a 0.7-MW (2,500,000 Btu/hr) commercial package boiler. Carbon monoxide (CO) emissions for these burner characterization tests indicated combustion efficiencies (CEs) greater than 99%. The low NO_x precombustor was then used to examine the co-firing characteristics of a nitrogenated pesticide, containing dinoseb (2-sec-butyl-4,6 dinitrophenol) in a fuel oil/xylene solvent. The dinoseb formulation as fired contained 6.4% nitrogen. NO emissions without in-furnace NO_x control exceeded 4400 ppm (@ 0% O_2). When NO_x controls in the form of air staging and natural gas reburning were employed, these emissions were reduced to below 150 ppm (96% reduction). Average CO and total hydrocarbon (THC) emissions were typically less than 15 and 2 ppm, respectively. Although no dinoseb was detected in any emission sample, and the destruction efficiency (DE) was greater than 99.99%, bioassay of the emission samples using the Salmonella (Ames) mutagenicity assay indicated the likely presence of nitroaromatics. The mutagenicity studies of the dinoseb emissions also showed that reburning (used for NO_x control) reduced the mutagenic emission factor by approximately 75% from that with air staging alone, even though reburning had little additional effect on NO_x emissions compared to air staging alone. In addition, the mutagenic emission factor with reburning was found to be similar to that for the residential burning of oil for heating.

INTRODUCTION

Oxides of nitrogen (NO_x) are formed during combustion by the thermal fixation (oxidation) of atmospheric nitrogen (N_2) (source of thermal NO_x) (Zeldovich et al., 1947) and by oxidation of nitrogen chemically bound in the fuel (source of fuel NO_x) (Pershing and Wendt, 1977). The U.S. Environmental Protection Agency (EPA) has designated nitrogen dioxide (NO_2) as a criteria pollutant because of its adverse effects on human health (CAA, 1977). NO_x emitted from stationary and mobile combustion sources contribute to the degradation of air quality and visibility as well as to acid deposition and forest damage (Keinhorst, 1986).

Thermal NO_x can be reduced by decreasing peak flame temperatures. Fuel NO_x, which is not as strongly dependent on temperature, is highly sensitive to reactant stoichiometry. Fuel-rich (substoichiometric) conditions promote N_2 formation over nitric oxide (NO) formation. Thus, many of the NO_x control technologies currently in use by coal- and oil-fired utility and industrial boilers involve modifications of the combustion process to reduce peak flame temperatures and create fuel-rich conditions by reducing fuel and oxidizer mixing rates. These combustion modifications, however, have the potential to reduce combustion efficiencies (CEs), increase combustor wall corrosion and ash deposition, and increase the emissions of organic products of incomplete combustion (PICs). Furthermore, practical constraints, such as burner and boiler sizes, sometimes limit the effectiveness of NO_x control by combustion modification.

The U.S. EPA has been involved in the development of two evolving advanced in-furnace NO_x control technologies: the precombustion chamber burner (utilizing air staging) and reburning. These two advanced combustion modification

techniques provide potential alternatives to post-combustion NO_x control technologies, such as selective catalytic reduction (SCR), which is being utilized extensively in Japan and West Germany. The precombustion chamber utilizes air staging whereby a portion of the air necessary for combustion is diverted to a location downstream of the primary flame. This configuration produces an initial fuel-rich zone which promotes NO and fuel nitrogen conversion to N_2. The remaining air is then added to complete the combustion process. Reburning (or fuel staging) is another combustion modification used for NO_x control whereby portions of both fuel and air are diverted to locations downstream of the primary flame. Under this configuration, three zones of different stoichiometry are established and adjusted to minimize NO_x formation. NO_x reduction via reburning occurs both by combustion of a portion of the fuel under fuel-rich stoichiometries (conditions promoting N_2 formation), and chemical destruction mechanisms involving secondary flame radical reactions with NO, resulting in N_2 formation. Mulholland et al. (1987) have shown that 50% NO_x reduction is possible with 15 to 20% of the fuel used for reburning. At low primary NO_x levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve measurable NO_x reduction. Although air staging and reburning are typically not applied simultaneously, Mulholland et al. (1987) showed that reburning can be used in conjunction with other NO_x control schemes, such as air staging, to yield lower NO_x emissions.

The precombustion chamber burner has been tested at full-scale on a 16 MW crude-oil-fired steam generator used for thermally enhanced oil recovery (TEOR) (England et al., 1985). A 30-day continuous monitoring test using heavy residual oil containing about 0.8% nitrogen demonstrated the burner's ability to maintain a nominal NO_x emission of 70 ppm (@ 3.0% O_2) and high combustion efficiency. During burner optimization testing, NO_x, carbon

monoxide (CO), and smoke emissions were measured over a range of first-stage stoichiometries. These data indicated the sensitivity of NO_x emission to first-stage stoichiometry and the efficient hydrocarbon burnout characteristics of the burner. Disadvantages of the original precombustion chamber design are its large size and weight and its slow response to load changes. Reburning is also currently being demonstrated at full-scale in several projects sponsored by EPA, U.S. Department of Energy, Electric Power Research Institute, and Gas Research Institute.

Numerous previous reports and research papers have reported on the results of these technologies applied to coal and heavy oil combustion systems of various sizes (Mulholland and Lanier, 1985; England et al., 1984; England et al., 1985; Mulholland and Hall, 1985, 1986; Greene et al., 1985; McCarthy et al., 1986; Mulholland et al., 1987; Mulholland and Srivastava, 1986, 1988; Pershing et al., 1989; Brown et al., 1990; Srivastava, 1990; LaFlesh et al., 1990). The goals of the experimental program reported here were to evaluate the precombustion chamber burner and reburning concepts during the co-firing of nitrogenated wastes. Specifically, this study used the EPA pilot-scale low NO_x precombustor burner and package boiler simulator to (a) verify low-NO_x emissions and high combustion efficiency; (b) determine the waste destruction efficiency (DE) and particulate emissions; (c) qualitatively identify a limited number of products of incomplete combustion (PICs), including potential nitrogenated PICs; and (d) examine the mutagenic activity of the emission samples, and compare the results to other combustion emissions.

Although co-firing and incineration of these materials may not produce a significant increase in the overall national NO_x emission levels, individual boiler or incinerator emissions may be sufficient to result in a local NO_x

problem, thereby preventing on-site thermal destruction from being permitted. With thermal destruction becoming an increasingly attractive alternative to landfill storage, there continues to be a need for developing high efficiency, low NO_x combustion technologies.

EXPERIMENTAL APPARATUS

The precombustion chamber burner is a staged combustion technology capable of achieving NO_x emissions of less than 0.1 lb (as NO_2)/10^6 Btu (0.043 g/MJ or approximately 90 ppm NO_x), even with high nitrogen content fuels (England et al., 1984). The pilot-scale experimental facility described by Mulholland and Srivastava (1988) and shown schematically in Figure 1 consists of a vertical low NO_x precombustion chamber burner and a horizontal water-tube package boiler simulator. A conventional high-swirl burner with primary air and fuel injection systems provides substoichiometric primary air and fuel/waste to the precombustion chamber. The chamber itself is made of several 0.25-m long spool sections with 0.51-m inside diameter. The modular design of the precombustor permits variation in nominal first-stage residence time between 250 and 750 ms. The sections have a thick refractory wall lining to minimize heat loss and maintain high (near adiabatic) temperatures that promote conversion of fuel nitrogen to N_2 under fuel-rich stoichiometries. A convergent elbow section minimizes back-mixing of combustion gas and radiation losses to the boiler. A water-cooled transition section (0.25-m inside diameter) cools the combustion gas before secondary air addition to minimize thermal NO_x generation.

The pilot-scale boiler simulator is rated at 0.9 MW (3,000,000 Btu/hr) thermal input. The boiler's radiant section is horizontal, 0.6-m inside diameter, 3.0-m long, and cooled with Dowtherm G heat transfer fluid. The burner transition section allows for radial addition of staged air. Additionally,

the boiler's front face has two ports for addition of staged (reburning) fuel at an angle of 45 degrees off axis and six axial ports for the addition of burnout air (see Figure 1). This design allows for reburning application from the boiler front face, with aerodynamic separation of the fuel-lean, fuel-rich, and fuel-lean zones in the boiler.

EXPERIMENTAL APPROACH

The experimental program was divided into burner evaluation and nitrogenated waste co-firing phases. The burner evaluation tests were designed to evaluate the system's performance using conventional natural gas and oil fuels doped with nitrogen-containing compounds to simulate nitrogenated waste co-firing conditions. Natural gas, doped with ammonia (NH_3) to yield a 0 to 5.8% fuel nitrogen content, and No. 2 distillate fuel oil, doped with pyridine (C_5H_5N) to yield a 0.01 to 5.0% fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures.

Burner baseline performance (air staging) and burner operation with reburning (fuel staging) were evaluated. Operational parameters examined included first-stage stoichiometry, exhaust stoichiometry (excess air), load, fuel nitrogen content, and percent fuel staging (reburning). The residence time of combustion gas in the burner is another important parameter that depends on precombustion chamber length, load, and stoichiometry. For these evaluation tests with doped fuels, we used the shortest burner configuration (worst case), which corresponded to a nominal residence time of 250 ms. The nominal system load was 0.6 MW (2,000,000 Btu/hr). A 0.7 MW (2,500,000 Btu/hr) North American (N.A.) fire-tube package boiler was used to provide conventional burner results for comparison with the multistaged burner results. This boiler is a three-pass unit with a continuous service rating of 0.3 kg

of steam per second (2400 lb/hr). Its size and thermal characteristics are similar to those of the package boiler simulator (Mulholland and Hall, 1987). Performance was monitored using a bank of continuous emission monitors (CEMs) for the measurement of combustion gases NO, NO_x, O_2, CO, CO_2, and total hydrocarbons (THC).

Subsequent to the burner evaluation tests, a second set of nitrogenated waste co-firing tests were conducted to examine the performance and emissions while firing a nitrogenated pesticide containing dinoseb (2-sec-butyl-4,6 dinitrophenol) in a fuel-oil/xylene solvent. The burner was configured with all its modular sections in place so as to maximize the first stage residence time (approximately 750 ms). This dinoseb pesticide product formulation as fired contained 6.4% nitrogen by weight. Elemental and compositional analyses of the dinoseb product and No. 2 fuel oil fuels are shown in Table 1. Combustion conditions without NO_x control, with air staging, and with air staging and reburning were evaluated using the low NO_x burner and package boiler simulator. The North American boiler was not used for these tests. Natural gas was used as the reburning fuel and was added in addition to a fixed primary load of 0.6 MW (2,000,000 Btu/hr). This increase in total load (approximately 32%) differs from the procedure used during the burner evaluation tests where total load was held constant. These tests included similar CEM measurements; determination of the particulate concentrations; characterization of the volatile organic fraction by GC/MS method; analysis of the semivolatile and nonvolatile organic fractions by GC/FID (total chromatographable organics, TCO), gravimetric (GRAV), and GC/MS techniques [including quantitative dinoseb concentrations for destruction efficiency (DE) calculations]; analysis of the semivolatile organic fraction for nitrated polycyclic aromatic hydrocarbons (NO_2-PAH) and hydroxylated-nitrated polycyclic aromatic hydrocarbons (OH-NO_2-PAH)

by HPLC/NCI (high pressure liquid chromatography/negative chemical ionization) GC/MS method; and characterization of the particulate inorganic fraction by x-ray diffraction.

The volatile organic fraction is operationally defined as those compounds collected by the volatile organic sampling train (VOST) method (Hansen, 1984). These compounds typically include those with boiling points less than 100°C. The semivolatile organic fraction is defined as those compounds that pass through an unheated filter and are collected on XAD-2 resin using a modified source assessment sampling system (SASS) (EPA Method 0020, 1986). These compounds typically include those with boiling points between 100 and 300°C. The nonvolatile organic fraction is defined as those organic compounds that remain on the SASS paticulate filter and typically include compounds with boiling points greater than 300°C. Filter or particulate samples typically contain both nonvolatile extractable organics and nonextractable inorganic material. However, for these tests, SASS samples were taken from the hot stack effluent (775 to 1025°C) through a 1-m unheated and uncooled isokinetic quartz sampling probe. This procedure causes the SASS filter to operate at temperatures greater than 300°C. Therefore, many nonvolatile organic compounds can be expected to be collected by the XAD-2 resin, which was maintained at 20°C.

In addition to the chemical analyses, portions of the emission samples were analyzed by bioassay techniques to determine toxic and mutagenic effects. Specifically, the Salmonella (Ames) mutagenicity assay (Maron and Ames, 1983) was used to evaluate the mutagenic activity of dichloromethane (DCM) as well as methanol (MEOH) extracts of the filters and XAD-2 resins. Because dinoseb is a nitroaromatic compound, it was assumed that some of the PICs may also be

nitroaromatic compounds, many of which are mutagenic in Salmonella. Therefore, in addition to a standard strain of Salmonella (strain TA98), two additional strains (strains TA98NR and TA98/1,8-DNP_6) were used that are deficient in nitroreductase or transacetylase, respectively, which are enzymes necessary for the conversion of nitroaromatics to electrophilic species that are mutagenic (arylhydroxyamines). By comparing the mutagenic activity obtained between the various bacterial strains, estimates can be made regarding the proportion of the total mutagenic activity that may be attributed to nitroaromatics.

Finally, mutagenic emission factors (mutagenic activity per unit weight or unit heating value of fuel) were calculated to determine the effect of dinoseb co-firing and in-boiler NO_x control strategies on mutagenic activity and to compare these values to those from other combustion processes, such as residential wood or oil burning, and industrial or utility boilers. Such information can provide a relative measure of the mutagenic and potential carcinogenic risks posed by various combustion processes.

The VOST method (Hansen, 1984) in conjunction with GC/MS analysis was used to characterize emissions of volatile organics. A modified SASS (EPA Method 0020, 1986) train in conjunction with GC/FID (TCO), GRAV (Lentzen et al., 1978), GC/MS, HPLC/NCI GC/MS (Nishioka et al., 1988), and x-ray diffraction analyses were used to characterize emissions of dinoseb, semivolatile and nonvolatile organics, and inorganic species.

Dinoseb recovery was determined by spiking 100 g of XAD-2 resin blanks with standard dinoseb solutions in DCM. These XAD-2 blanks were Soxhlet extracted in DCM and then concentrated (Lentzen et al., 1978). The concentrated extract was then analyzed by GC/MS.

Each SASS filter was extracted three times (10 min. each) with 100 ml of MEOH by a sonication procedure (Williams et al., 1988), and the three extracts were combined. Each filter was then extracted three more times with DCM, and these three extracts were combined, but kept separate from the MEOH extracts. Each SASS XAD-2 sample was extracted for 24 h with 2500 ml of MEOH by a Soxhlet procedure (Williams et al., 1988). Each XAD-2 sample was then again extracted by this procedure with DCM. Finally, each of the two extracts (MEOH and DCM) per filter and per XAD-2 sample was filtered through 0.45 um filters and rotary evaporated at 35°C to approximately 8 ml.

Each MEOH extract was then back-extracted three times with DCM by first reducing the volume of each MEOH extract to 2-3 ml and transferring to a separatory funnel. Then 50 ml of distilled deionized water and 20 ml of DCM were added, the funnel was shaken, and the DCM phase was added to the original DCM extracts. Following this, each MEOH extract was acidified with sulfuric acid to a pH of 2 and was again back-extracted three times with DCM. These extracts were again added to the original DCM extracts. Each DCM extract was then rotary-evaporated and redissolved in 10 ml of DCM.

These procedures were performed to concentrate both polar and nonpolar organic compounds in the DCM extract and resulted in 10 ml each of a MEOH and DCM extract for each filter and for each XAD-2 sample. Three ml of each sample was used for GC/FID (TCO), GRAV, GC/MS, and HPLC/NCI GC/MS analyses. The remaining 7 ml was placed under nitrogen and solvent-exchanged into dimethyl sulfoxide (DMSO) for bioassay (Williams et al., 1988).

Samples were evaluated for mutagenicity using the plate-incorporation assay in strains TA98, TA98NR, and TA98/1,8-DNP_6 of Salmonella typhimurium according to the procedures of Maron and Ames (1983). Strain TA98 was obtained from

B.N. Ames, Biochemistry Department, University of California, Berkeley, CA. The other two strains were obtained from H.S. Rosenkranz, Department of Environmental Health Sciences, School of Medicine, Case Western Reserve University, Cleveland, OH. Nitroaromatic compounds are direct-acting mutagens in Salmonella; i.e., they do not require addition of a metabolic activation system (S9) in order to be mutagenic. Because dinoseb is a nitroaromatic compound, and its combustion would likely result in nitroaromatic PICs, S9 was not used in these studies.

All samples were first evaluated at five doses using one plate per dose due to limited sample size. The repeated experiments were performed with two plates per dose. Samples were considered mutagenic if they gave a reproducible, dose-related increase in the number of revertants per plate compared to the control (DMSO) plates. Linear regressions over the linear part of the dose/response curves were calculated to determine the mutagenic potency (rev/ug or rev/m^3) of each sample.

RESULTS AND DISCUSSION

Burner Evaluation

Figure 2 summarizes the effects of variations of first-stage stoichiometry, exhaust stoichiometry (excess air), and fuel/waste nitrogen content on NO emissions. Nominal or base case conditions for these tests were optimal first-stage stoichiometry (SR1) of 0.78 for NH_3/natural gas and 0.65 for C_5H_5N/fuel oil, excess air of 15%, and fuel nitrogen contents of 5.8% for NH_3/natural gas and 2.0% for C_5H_5N/fuel oil. Corresponding NO emissions from the North American (N.A.) boiler are also presented. Figure 2a illustrates the extreme sensitivity of first-stage stoichiometry (SR1) on the NO produced. The effect of excess air on stack NO is shown in Figure 2b. In contrast to

the N.A. boiler, NO emissions from the low NO_x precombustor are relatively insensitive to variations in excess air. Figure 2c shows similar behavior with respect to variations in fuel/waste nitrogen content. Comparison of NO emissions from the two units at similar test conditions indicates that, without additional reburning, the low NO_x burner reduced NO emissions by about 68 and 75%, respectively, for the NH_3/natural gas and C_5H_5N/fuel oil base case tests.

For the burner evaluation reburning tests, total boiler load (0.6 MW, 2,000,000 Btu/hr) was held constant, while 35% of the fuel was diverted from the primary fuel injector to two secondary injectors. The reburn fuel (undoped natural gas) and burnout air were added through ports in the boiler front face as discussed previously (see Figure 1). The C_5H_5N/fuel oil and NH_3/natural gas tests examined two second-stage stoichiometries (SR2) (1.1 and 1.0). The data (dry, corrected to 0% O_2) indicate that exhaust NO levels were reduced to 120 ppm (from 190 ppm) at a SR2 of 1.1 (SR3 = 0.76) and to 110 ppm at a SR2 of 1.0 (SR3 = 0.69) for the 2.0% nitrogen C_5H_5N/fuel oil tests. Similarly, NO emissions were reduced to 195 ppm (from 315 ppm) at a SR2 of 1.1 (SR3 = 0.72) and to 160 ppm at a SR2 of 1.0 (SR3 = 0.65) for the 5.8% nitrogen NH_3/natural gas tests. Overall excess air for all tests was maintained at 15% (SR4 = 1.15). Under reburning conditions, NO emissions decreased due to primary NO destruction and combustion gas dilution (fuel substitution).

Note that, for these tests, dilution accounts for most of the NO decreases measured. This is likely due to the relatively low NO levels to begin with (from the procombustion chamber) and to less distinct stoichiometric zones than are typically established in reburning applications. Mulholland and Hall (1987) have shown that NO is reduced when additional boiler penetrations

are made to allow the staged fuel to be injected farther downstream of the fuel-lean second-stage zone. However, the configuration used in these tests requires no additional boiler penetrations other than modifications to the boiler front face. In addition, complete destruction of the primary fuel/waste stream appears to be promoted by providing all of the required primary combustion air near the boiler entrance.

Relatively low NO_x emission levels were possible with a shortened precombustion chamber burner provided the first-stage stoichiometry was optimized. These results demonstrate the precombustion chamber burner's ability to reduce fuel nitrogen to N_2 even at reduced residence times (250 ms). The full size (600 to 800 ms) precombustion chamber burner produces NO emissions that are even less sensitive to fuel nitrogen content (England et al., 1984). For all the tests performed during burner performance evaluation, CO emissions were less than 35 ppm, indicating that combustion efficiencies were greater than 99%.

Nitrogenated Waste Co-firing

Successively increasing concentrations of dinoseb product in No. 2 fuel oil were co-fired to determine the maximum dinoseb product concentration in No. 2 distillate fuel oil for stable operation. These tests revealed that 100% dinoseb product could be stably combusted. Thereafter, the remaining tests were performed with 100% dinoseb product. The experimental matrix summarizing the nitrogenated waste co-firing tests is shown in Table 2.

Table 2 also presents the precombustor and reburning stoichiometries (SR1-4), CEM measurements, and particulate emission data for the dinoseb product co-firing tests. All CEM concentrations (except for O_2) are presented dry, corrected to 0% O_2. Particulate loadings are corrected to 7% O_2 as per RCRA convention (RCRA, 1984). Test 5 indicated that NO emissions without any

combustion modification for NO_x control exceeded 4400 ppm. When NO_x controls in the form of air staging with and without natural gas reburning were applied, these NO emissions were reduced to below 150 ppm. Thus, the use of the precombustor reduced the NO emissions by approximately 96%. It is interesting to note that reburning did not offer any further NO_x reduction than air staging alone. This is likely because the configuration of the experimental facility provided ample first-stage residence time for the conversion of fuel nitrogen to N_2 and further allowed secondary air addition at relatively cool temperatures, thus inhibiting the formation of thermal NO. These effects likely provided a low concentration of NO before the addition of reburning fuel and so inhibited reburning efficiency (Mulholland et al., 1987).

It is interesting to note that the NO_x measurements were similar to those for NO. In fact, the differences are well within instrument error. This addresses a concern that, because of the nature of dinoseb, NO_2 may be preferentially emitted. It is, however, shown to be consistent with other nitrogen-containing fuels tested, that NO_2 is typically less than 5% of the total NO_x emitted. It is also important to note that corresponding NO emissions from uncontrolled dinoseb product combustion in industrial boilers would likely be somewhat less than that measured in test 5. The high temperature, adiabatic design of the precombustor promotes thermal NO_x formation when operated fuel-lean. This type of operation, however, is comparable to that used in most hazardous waste incinerators (high temperatures, adiabatic, high excess air, high residence times) and so is of practical interest.

The particulate emissions for all tests were below the RCRA limit of 180 mg/dsm^3 (RCRA, 1984). An x-ray diffraction analysis determined that the

particulate collected on the SASS filters consisted primarily of calcium sulfate and calcium oxide. The particulate emission level for dinoseb product combustion with reburning was less than that for dinoseb product combustion without reburning. This may be partially due to increased carbon burnout, but is most likely due to simple dilution by the addition of a premium (natural gas) reburn fuel and oxidizer. The CO and unburned hydrocarbon (THC) emissions were less than or equal to 15 and 2 ppm, respectively, indicating that the combustion efficiencies were in excess of 99%.

Table 3 presents the results of TCO and GRAV analyses of the organic extracts (filter and XAD-2). These data, compared with Table 2, indicate that (although the organic extracts were typically 50 and 10% of the particulate collected for the fuel oil and dinoseb tests, respectively) less than 2% of this organic material was TCO range. In other words, more than 98% of the extracted organic material consisted of heavier organic compounds difficult to identify by cursory GC/MS techniques. Table 3 also indicates that in most cases the XAD-2 sample fraction contained the majority of the organic material. This is consistent with the sampling procedure in which the SASS filter was operated at relatively high temperatures.

No dinoseb was detected in any of the SASS samples. These combined filter, probe rinse, and XAD-2 extracts were analyzed by GC/MS. These results and the results of dinoseb recovery tests are shown in Table 4. The data indicate that, although the DCM extraction method used resulted in low dinoseb recovery (9.39%), destruction efficiencies (DEs) greater than 99.99% could be calculated using recovery measurements and measured GC/MS instrument dinoseb detection limits (10 ng/ul). Low dinoseb recoveries, however, are not unique to these tests. Concurrent research activities sponsored by EPA's Risk

Reduction Engineering Laboratory (RREL) and Health Effects Research Laboratory (HERL) found similar results (Wool et al., 1988). These tests showed acetone to be a somewhat better solvent compared to both MEOH and DCM, although recoveries using acetone were also relatively low. It is unknown whether this low dinoseb recovery is due to poor solubility off the XAD-2 resin into the various solvents, or whether the extraction process causes molecular degradation.

Qualitative PIC emissions, measured by VOST sampling in conjunction with GC/MS analysis, are shown in Table 5. Results indicate that several common combustion PICs were present and were emitted in concentrations typically less than 10 ppb. It is important to note that these analyses include only qualitative identification and quantification of volatile compounds. Cursory examination of the TCO range organic fraction (SASS samples) by GC/MS analysis adds little in the way of additional qualitative information, although numerous unidentified minor peaks were observed. The TCO range organic material typically comprised less than 2% of the total organic material (see Table 3). Higher molecular weight compounds (GRAV range, boiling points > 300°C) including polycyclic aromatic hydrocarbons (PAHs) by GC/MS could not be identified due to instrument limitations. This was unfortunate because over 98% of the total organic material was found in the GRAV range (see Table 3).

In a further effort to identify potential nitrogenated PICs (including GRAV range species) that might be formed during dinoseb combustion, a portion of the XAD-2 DCM extract from test 4 (dinoseb product combustion with air staging and reburning) was analyzed for NO_2-PAHs and OH-NO_2-PAHs by HPLC/NCI GC/MS (Nishioka et al., 1988). The data (Table 6) indicate that few of the NO_2-PAH and OH-NO_2-PAH compounds examined for were detected, and several others

were detected below quantifiable limits. Concentrations of those compounds quantified corresponded to low ppb levels in the stack gases.

Neither the MEOH nor the DCM extracts of the filters were mutagenic (data not shown), probably because the effluent was collected at temperatures where the organics did not condense on the particulate phase. Instead, mutagenic activity was found only in the XAD-2 samples. Initial studies in the three bacterial strains with the MEOH extracts of the XAD-2 samples revealed the presence of only slight mutagenic activity (data not shown). Thus, no further studies were performed with these extracts.

However, the DCM extracts from the XAD-2 samples gave dose/response curves that permitted the calculation of mutagenic potencies (rev/ug or rev/m^3) among the three strains (Table 7). The results in strain TA98, which would detect direct-acting mutagens such as nitro-PAHs, indicated that the No. 2 fuel oil blanks with and without reburning (Tests 1 and 2) produced mutagenic emission factors between those reported by Lewtas (1988) from industrial and utility oil combustion systems and residential oil furnaces. The dinoseb combustion tests (Tests 3 and 4) produced mutagenic emission factors several orders of magnitude greater than the values reported for industrial utility boilers and power plants (Lewtas, 1988). However, these values are at least one or two orders of magnitude less than those reported for residential burning of wood for heat (Lewtas, 1988) or for the field burning of agricultural plastic (Linak et al., 1989). Such an analysis permits the potential health effects from the combustion of dinoseb (or any fuel or waste stream) to be placed in perspective to those from other combustion systems.

Table 7 also indicates that reburning decreased the mutagenic potency of the DCM-extractable organics from the XAD-2 by approximately 75% (Test 3 without

reburning vs. Test 4 with reburning). This interpretation must be made with care based on the limited data, and because these data have not been corrected for any dilution effect caused by the addition of natural gas, a premium reburning fuel. However, dilution correction would be unlikely to account for a 75% decrease. The secondary flame front caused by reburning may promote more complete oxidation of PICs formed in the precombustor and boiler burnout sections. Table 7 shows that the amount of mutagenic activity emitted from the combustion of dinoseb with reburning (1.89-3.07 rev/kg fuel x 10^5 or 5,520-8,940 rev/MJ) was similar to that emitted from residential burning of oil for heating (1 rev/kg fuel x 10^5 or 2,500 rev/MJ) (Lewtas, 1988).

Because dinoseb is a dinitroaromatic compound, it was likely that nitroaromatics would be present in the PICs. The use of the strains TA98NR and TA98/1,8-DNP_6 permits an estimate of the amount of mutagenic activity that may be due to mono- and dinitroaromatic compounds. Strain TA98NR is deficient in the "classical" nitroreductase, which is present in strains TA98 and TA98/1,8-DNP_6 (McCoy et al., 1983). Thus, 1-NO_2-pyrene, for example, is less mutagenic in this strain than it is in the other two strains. Consequently, if a complex mixture is less mutagenic in strain TA98NR than it is in strain TA98, then the mixture can be assumed to contain some mutagenic mononitroaromatics such as 1-NO_2-pyrene.

Strain TA98/1,8-DNP_6 is deficient in an arylhydroxylamino-transacetylase, which is present in strains TA98 and TA98NR (McCoy et al., 1983). Thus, compounds such as 2-NO_2-fluorene, N-OH-2-aminofluorene, 1,8-NO_2-pyrene, and 5-NO_2-acenaphthene are less mutagenic in this strain than they are in the other two strains. Consequently, if a complex mixture is less mutagenic in strain TA98/1,8-DNP_6 than it is in strain TA98, then the mixture can be assumed to

contain some mutagenic dinitroaromatics such as 1,8-NO_2-pyrene or other compounds listed above.

Without reburning, the mutagenic potencies and mutagenic emission factors of the dinoseb PICs were only slightly less in strain TA98NR compared to TA98, but they were reduced by 72% in strain TA98/1,8-DNP_6 (Table 7, Test 3). Thus, nearly 75% of the mutagenic activity of the PICs is due to compounds such as dinitroaromatics. Such a finding is not surprising considering that dinoseb itself is a dinitroaromatic.

With reburning, the mutagenic potencies and mutagenic emission factors of the dinoseb PICs were reduced by approximately 70% in strain TA98NR and by approximately 90% in strain TA98/1,8-DNP_6 (Table 7, Test 4). Thus, most of the mutagenic activity of the PICs produced with reburning was due to the presence of mono- as well as dinitroaromatics. Although reburning reduced the overall mutagenic potency and mutagenic emission factors of the dinoseb PICs, more of the mutagenic activity of the PICs produced by reburning was due to nitroaromatics compared to that produced without reburning. This is consistent with the notion that the presence of nitrogen and oxygen during reburning would create conditions favorable to the introduction of nitro-moieties onto aromatic compounds.

Table 6 indicates the presence of some nitroaromatic compounds. Of those that were present in the DCM extract of the XAD-2 sample from Test 4, several are mutagenic in strain TA98, including 3-NO_2-phenol, 6-CH_3-3-NO_2-phenol, 2-CH_3-4-NO_2-phenol, and 2-OH-1-NO_2-naphthalene (Lewtas, unpublished results). The concentrations of these compounds in the DCM extract (1-10 ug/ml) permit a calculation of the concentration of these compounds on the petri plates in the present experiments (0.04-0.4 ug/plate). The results show that these

compounds must be present at concentrations of 60-180 ug/plate in order to be mutagenic.

Thus, individually, none of these nitroaromatics could have accounted for the observed mutagenic activity. However, additive and/or synergistic interactions amoung these compounds may have produced some mutagenic activity, and many other mutagens were likely present in the PICs. Thus, the chemical analysis did not identify many of the chemicals that account for the mutagenic effects of the PICs. This illustrates the value of using both chemical and biological analyses to characterize PICs. By fractionating a complex mixture such as PICs and performing bioassay-directed chemical analysis, some of the chemical classes responsible for much of the biological activity can be identified (Lewtas, 1988).

SUMMARY

Results from the burner evaluation experimental tests indicate that a precombustion chamber burner, shortened in length, is effective in minimizing NO_x emissions and is capable of providing an overall NO reduction of approximately 85%. These observations were confirmed in the dinoseb co-firing tests with the lengthened burner, where NO_x reductions of approximately 96% were obtained.

The reburning hardware modifications used in this study were designed with retrofit feasibility and efficient combustion in mind. In the reburning tests performed during both test phases, staged fuel and air from the front face of the boiler provided a secondary flame for increased primary fuel/waste destruction. However, in these tests, reburning used in combination with air staging did not yield significant additional NO_x reduction compared to that realized by air staging alone other than the reduction caused by dilution.

Mutagenic emission factors of the fuel oil combustion blanks were comparable to those from utility and industrial oil combustion determined from other studies (Lewtas, 1988). Mutagenic emission factors of the dinoseb tests were somewhat higher, but remained one or two orders of magnitude less that those measured from the residential burning of wood for heat (Lewtas, 1988) or the open burning of agricultural plastic (Linak et al., 1989).

Although reburning reduced the mutagenic potency of the organics compared to air staging alone, a greater proportion of these organics were presumptively nitroaromatic mutagens. The mutagenic emission factor for the dinoseb tests with reburning compared well to those from the residential burning of oil for heat (Lewtas, 1988).

The results of this program indicate that precombustion chamber burner technology is capable of combusting nitrogenated wastes with DEs in excess of 99.99%; maintaining low NO_x, THC, and PIC emissions; producing combustion efficiencies in excess of 99%; and producing relatively low mutagenic emission factors compared to other common combustion sources. This technology may, therefore, be an attractive alternative for the disposal/destruction of nitrogenated wastes.

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DISCLAIMER

The research described in this paper has been reviewed by the Air and Energy Engineering Research Laboratory and Health Effects Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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Table 1. Elemental and compositional analysis of dinoseb product and No. 2 fuel oil used for boiler co-firing tests.

Dinoseb Product				No. 2 Fuel Oil
Ultimate Analysis		Analysis from Material Safety Data Sheet		Ultimate Analysis
C	65.01 %	Dinoseb	54.4 %	C 86.44%
H	7.27 %	Diesel No. 2	4.04 %	H 13.21%
N	6.63 %	Xylene Range Aromatic	32.5 %	N 0.01%
O[a]	20.45 %			O 0.04%
S	0.35 %	Inert	9.06 %	S 0.22%
Ash	0.29 %			Ash <0.01%
Moisture	0.63 %			Moisture -
HHV	13,076 Btu/lb (30.41 MJ/kg)			HHV 18,177 Btu/lb (42.28 MJ/kg)

[a]Oxygen by difference

Table 2. Summary of operating conditions, CEM and particulate results.[a]

Test	Condition	NO_x Control	SR1[b]	SR2	SR3	SR4	R/P[c] (%)
1	No. 2 fuel oil combustion blank	Air staging	0.72	1.35	1.35	1.35	NA[d]
2	No. 2 fuel oil combustion blank	Air staging and reburning	0.62	1.14	0.87	1.20	32.5
3	Dinoseb product	Air staging	0.64	1.23	1.23	1.23	NA
4	Dinoseb product	Air staging and reburning	0.61	1.08	0.82	1.17	31.4
5	Dinoseb product	None	1.13	1.13	1.13	1.13	NA

Test	O_2 (%)	NO (ppm)	NO_x (ppm)	CO (ppm)	THC (ppm)
1	5.02	78	-	9	-
2	3.65	89	-	13	-
3	3.60	141	128	6	2
4	3.51	138	132	14	1
5	2.22	4401	4497	13	1

Test	Volume Sampled (dsm^3)	Particulate Collected (mg)	Part. Conc. (mg/dsm^3)	Part. Conc. at 7% O_2 (mg/dsm^3)
1	21.49	69.8	3.25	2.85
2	5.37	21.9	4.08	3.29
3	3.68	489.1	132.91	106.94
4	5.37	389.0	72.44	57.98
5[e]	-	-	-	-

[a]CEM measurements (except O_2) corrected to 0% O_2. CO_2 concentrations are not included due to instrument malfunction.
[b]SR1, SR2, SR3, SR4 indicate the stoichiometric ratios calculated at the combustor locations shown in Figure 1.
[c]R/P indicates gas reburning load/primary load (natural gas added in addition to constant primary burner load of 2×10^6 Btu/hr). CEM and particulate concentrations have not been corrected for this dilution.
[d]Not applicable.
[e]Test 5 included CEM measurements only.

Table 3. Summary of semivolatile and nonvolatile organic results.[a]

Test	Volume Sampled (dsm^3)	Sample Fraction	TCO Mass (mg)	TCO Conc. (mg/dsm^3)	TCO as % of Sample Fraction	GRAV Mass (mg)	GRAV Conc. (mg/dsm^3)	GRAV as % of Sample Fraction	Organic Extract TCO+GRAV (mg/dsm^3)	Sample Fraction as % of Organic Extract
1[c]	21.49	XAD-2	0.308	0.014	1.17	26.0	1.210	98.83	1.224	75.73
		Filter[b]	0.029	0.001	0.34	8.4	0.391	99.66	0.392	24.27
		Total	0.337	0.015		34.4	1.601		1.616	
2[d]	5.37	XAD-2	0.188	0.035	1.85	10.0	1.862	98.15	1.897	86.43
		Filter	0.000	0.000	0.00	1.6	0.298	100.00	0.298	13.57
		Total	0.188	0.035		11.6	2.160		2.195	
3[c]	3.68	XAD-2	0.320	0.087	1.96	16.0	4.348	98.04	4.435	44.40
		Filter	0.039	0.011	0.19	20.4	5.543	99.81	5.554	55.60
		Total	0.359	0.098		36.4	9.891		9.989	
4[d]	5.37	XAD-2	0.145	0.027	0.46	31.2	5.810	99.54	5.837	76.54
		Filter	0.007	0.001	0.07	9.6	1.788	99.93	1.789	23.46
		Total	0.152	0.028		40.8	7.598		7.626	
5[e]	-	-	-	-	-	-	-	-	-	-

Method Blank Values

	TCO Mass (mg)	GRAV Mass (mg)
XAD-2	ND[f]	6.4
Filter	ND	2.8

[a]TCO and GRAV values have not been corrected for method blank values.
[b]Filter samples include probe rinse.
[c]Sample fractions extracted with MEOH first then DCM. MEOH extracts back-extracted into DCM. TCO and GRAV value derived from combined DCM extracts.
[d]Sample fractions extracted with DCM first then MEOH.
[e]Test 5 included CEM measurements only.
[f]Not detected.

Table 4. Dinoseb analysis and destruction efficiency (DE) calculations.

Dinoseb Recovery Tests[a]

Test	Analysis Concentration (ng/ul)	Measured Concentration (ng/ul)	Recovery (%)
A	10	ND[b]	NA[c]
B	100	ND	NA
C	1000	93.9	9.39

Co-firing Tests

Test	Potential Max. Dinoseb Conc. in Sample (g, ng/ul)	Dinoseb Conc. Measured in Sample (ng)	DE Using 10 ng/ul Instrument Sensitivity,[a] 100% Recovery	DE Using 10 ng/ul Instrument Sensitivity,[a] 9.39% Recovery
1	0	ND	NA	NA
2	0	ND	NA	NA
3	162.15, 4.054×10^6	ND	>99.9998	>99.997
4	209.31, 10.466×10^6	ND	>99.9999	>99.999
5[d]	-	-	-	-

[a]Instrument sensitivity determined at 10 ng/ul.
[b]Not detected.
[c]Not applicable.
[d]Test 5 included CEM measurements only.

Table 5. Compounds identified through GC/MS analysis of VOST samples.

Test	Compound	ng[a]	ug/dsm^3	ppb
1	Benzene	2	<1	<1
2A	Benzene	37	2	<1
	SO_2	514	28	10.7
2B	Benzene	18	1	<1
	SO_2	414	22	8.4
3A	Benzene	12	1	<1
	Toluene	4	<1	<1
	Ethylbenzene	4	<1	<1
	Dodecane	22	1	<1
	Naphthalene	1725	91	17.4
3B	Benzene	2	<1	<1
	SO_2	125	7	2.7
4	Benzene	9	1	<1
	Toluene	10	1	<1

[a]Concentrations estimated using average system responses to benzene, toluene, and ethylbenzene.

Table 6. Nitrated aromatic and polycyclic compounds identified in XAD-2 fraction of test 4 (dinoseb product combustion with air staging and reburning).

Compound $OH-NO_2-PAH$	Conc. in Sample Extract (ug/ml)	Conc. in Exhaust Gases (ug/dsm^3)[a]	Compound NO_2-PAH	Conc. in Sample Extract (ug/ml)	Conc. in Exhaust Gases (ug/dsm^3)
$2-NO_2$-phenol	1	1.69	$2-NO_2$-toluene	2	3.39
$3-NO_2$-phenol	<1[b]	<1.69	1-NO2-naphthalene	0.5	0.85
$4-NO_2$-phenol	8	13.56	$2-NO_2$-naphthalene	<1	<1.69
$3-CH_3-2-NO_2$-phenol	ND[c]	-	2-NO2-biphenyl	0.5	0.85
$6-CH_3-2-NO_2$-phenol	ND	-	NO_2-biphenyl/ acenaphthalene	ND	-
$4-CH_3-2-NO_2$-phenol	ND	-	$2-NO_2$-fluorene	ND	-
$5-CH_3-2-NO_2$-phenol	ND	-	NO_2-fluorenone(345.0)	ND	-
$2-CH_3-3-NO_2$-phenol	<1	<1.69	NO_2-fluorenone(381.3)	ND	-
$4-CH_3-3-NO_2$-phenol	<1	<1.69	$9-NO_2$-anthracene	1	<1.69
$6-CH_3-3-NO_2$-phenol	<1	<1.69	NO_2-phenanthrene/ anthracene(356.1)	ND	-
$3-CH_3-4-NO_2$-phenol	<1	<1.69	NO_2-phenanthrene/ anthracene(365.9)	ND	-
$2-CH_3-4-NO_2$-phenol	1	1.69	NO_2-phenanthrene/ anthracene(371.1)	ND	-
2-OH-1-NO_2-naphthalene	10	16.95	NO_2-phenanthrene/ anthracene(380.2)	ND	-
1-OH-2-NO_2-naphthalene	ND	-	NO_2-phenanthrene/ anthracene(386.3)	ND	-
x-OH-y-NO_2-naphthalene(308.4)[d]	ND	-	$2/3-NO_2$-fluoranthene	<1	<1.69
x-OH-y-NO_2-naphthalene(319.2)	ND	-	NO_2-fluoranthene/ pyrene	ND	-
x-OH-y-NO2-naphthalene(325.9)	ND	-	$1-NO_2$-pyrene	<1	<1.69
1-OH-4-NO_2-naphthalene	5	8.47	NO_2-PAH MW 228(519.7)[e]	ND	-
1-OH-4-NO_2-methyl naphthalene (359.4)	ND	-	NO_2-PAH MW 179(217.1)[f]	46	77.97
x-OH-y-NO_2-biphenyl(273.1)	<1	<1.69			
4-OH-3-NO_2-biphenyl	<1	<1.69			
x-OH-y-NO_2-biphenyl(319.2)	<1	<1.69			
x-OH-y-NO_2-phenanthrene	ND	-			
Dinoseb isomer	ND	-			
Dinoseb	ND	-			
3-OH-1-NO_2-pyrene	ND	-			
6/8-OH-1-NO_2-pyrene	ND	-			
$OH-NO_2-PAH$ MW 211(614.5)	ND	-			

[a]Concentrations calculated from 10 ml total extract volume, 5.90 dsm^3 volume sampled.
[b]Detected, less than quantification limit.
[c]Not detected.
[d]Retention index value in parentheses.
[e]NO_2-substituted benz(a)anthracene, chrysene, triphenylene.
[f]NO_2-substituted acridine, benzoquinoline, benzoisoquinoline.

Table 7. Mutagenic potencies and mutagenic emission factors of XAD-2 organic extracts.

	Mutagenic Potency[a]					
	TA98		TA98NR		TA98/1,8-DNP_6	
Test	rev/ug	rev/m^3	rev/ug	rev/m^3	rev/ug	rev/m^3
1	0.18	218	-	-	0.04	49
2	0.97	1,806	0.40	745	0.10	186
	0.86	1,601	-	-	-	-
3	18.40	80,003	15.10	66,655	5.10	22,175
4	4.41	25,622	1.22	7,088	0.46	2,673
	2.72	15,803	-	-	-	-

	Mutagenic Emission Factor					
	rev/kg fuel x 10^5			rev/MJ[b]		
Test	TA98	TA98NR	TA98/1,8-DNP_6	TA98	TA98NR	TA98/1,8-DNP_6
1	0.05	-	0.01	110	-	20
2	0.31	0.13	0.03	645	266	66
	0.27	-	-	570	-	-
3	9.90	8.25	2.74	32,560	27,130	9,020
4	3.07	0.85	0.32	8,940	2,470	930
	1.89	-	-	5,520	-	-
Residential heating[c]						
Wood	50			250,000		
Oil	1			2,500		
Industrial and utility boilers and power plants[c]						
Oil	0.03			70		
Coal	0.06			230		
Wood	0.20			1000		
Field burning of agricultural plastic[d]	100			250,000		

[a]Mutagenic potencies are the slopes calculated from the linear portion of the dose/response curves (data not shown).
[b]Revertants per megajoule of heat.
[c]Taken from Lewtas (1988).
[d]Taken from Linak et al. (1989).

LIST OF FIGURES

Figure 1. EPA pilot-scale combustion research facility consisting of a refractory-lined precombustion chamber burner and package boiler simulator, with modified air and fuel staging ports.

Figure 2. Burner evaluation test results examining:

(a) Effect of first-stage (burner) stoichiometry on exhaust NO concentration from tests burning 5.8% fuel nitrogen NH_3/natural gas and 2% fuel nitrogen C_5H_5N/No. 2 distillate fuel oil mixtures at 15% excess air.

(b) Effect of excess air on exhaust NO concentration from tests burning 5.8% fuel nitrogen NH_3/natural gas and 2% fuel nitrogen C_5H_5N/No. 2 distillate fuel oil mixtures. Curves with open symbols represent data from the low NO_x facility operated at optimum first-stage stoichiometries as shown in Figure 2a. Curves with filled symbols represent corresponding data from the conventional North American (N.A.) boiler.

(c) Effect of fuel nitrogen content on exhaust NO concentration from tests burning NH_3/natural gas and C_5H_5N/No. 2 distillate fuel oil mixtures. Curves with open symbols represent data from the low NO_x facility operated at optimum first-stage stoichiometries as shown in Figure 2a. Curves with filled symbols represent corresponding data from the conventional North American (N.A.) boiler. All data taken at 15% excess air.

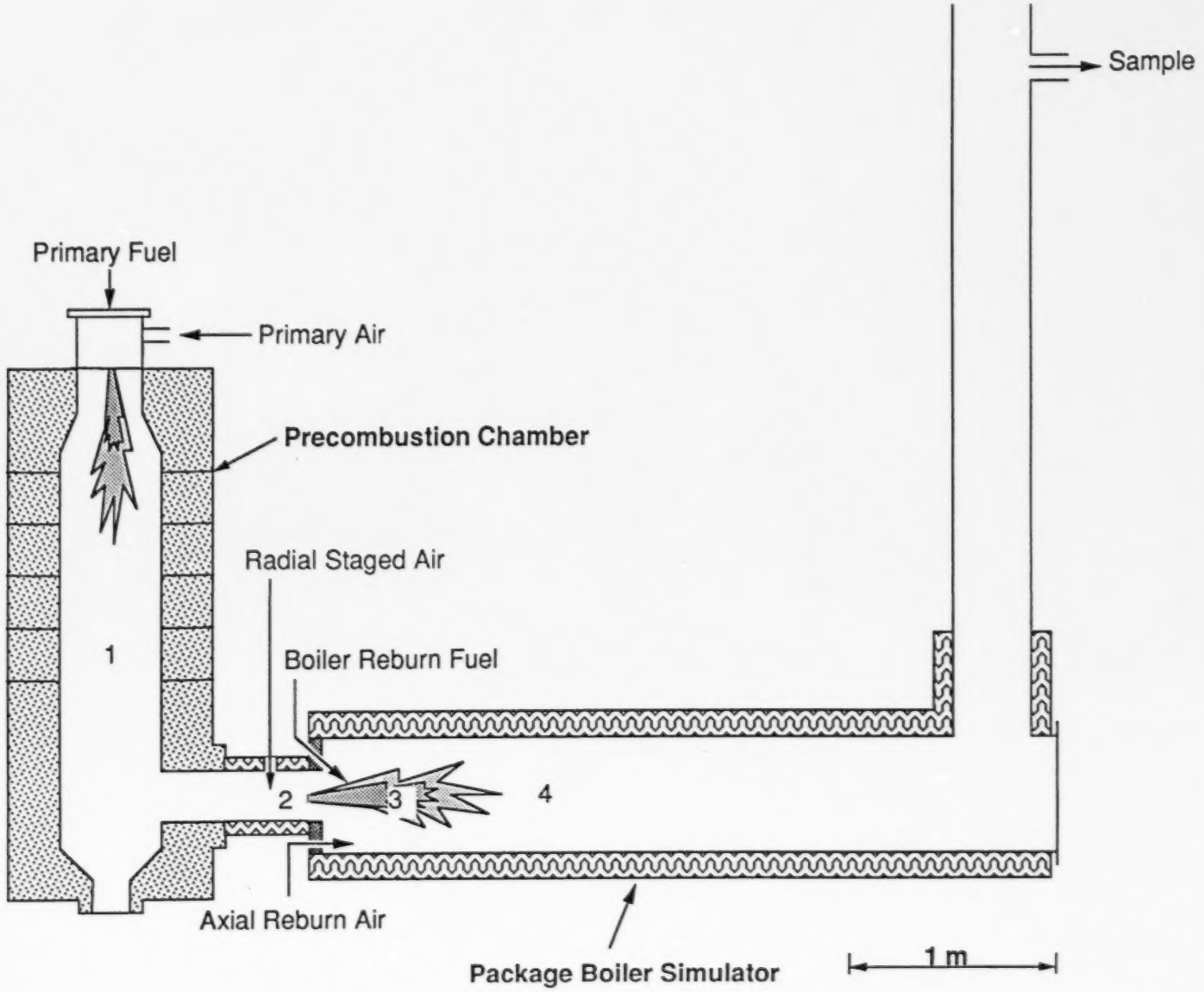
Sample
Primary Fuel
Primary Air
Precombustion Chamber
Radial Staged Air
1
Boiler Reburn Fuel
2
3
4
Axial Reburn Air
Package Boiler Simulator
1 m

Figure 1.

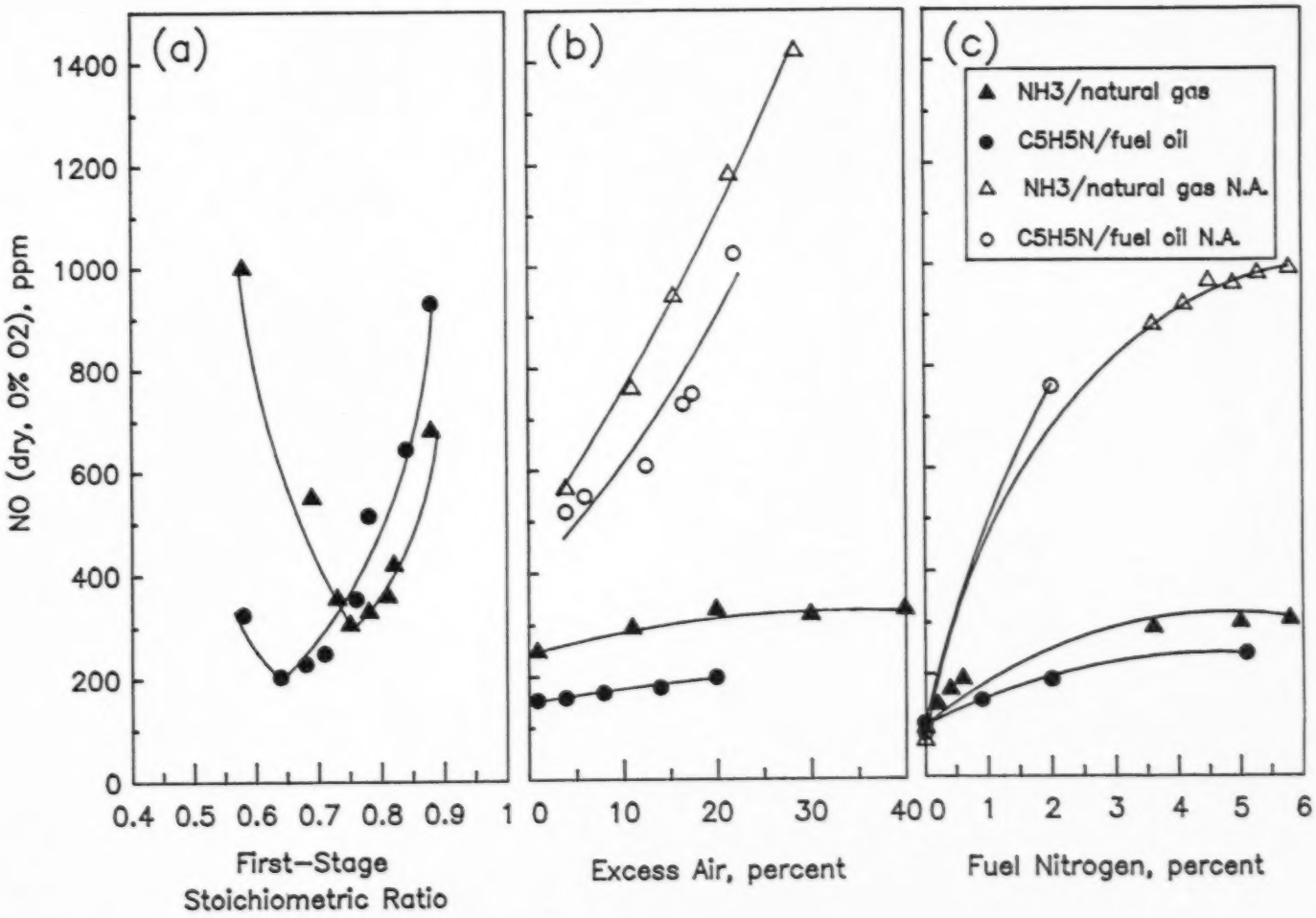
(a)
(b)
(c)
NO (dry, 0% 02), ppm
1400
1200
1000
800
600
400
200
0
0.4 0.5 0.6 0.7 0.8 0.9 1
First–Stage
Stoichiometric Ratio
0 10 20 30 40
Excess Air, percent
0 1 2 3 4 5 6
Fuel Nitrogen, percent
NH3/natural gas
C5H5N/fuel oil
NH3/natural gas N.A.
C5H5N/fuel oil N.A.

Figure 2.